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Art. VI.—*Description of a New Dividing Engine for Ruling Diffraction Gratings.*

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(With Plates VI.–XVII.)

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Introductory.

The following pages comprise a description of a New Dividing Engine designed and constructed by the writer for the ruling of Diffraction Gratings and also, with certain modifications, of accurate scales. Prior to 1910, when this work was begun, a considerable experience of the difficulties inherent to work of a related character had already been obtained; particularly with respect to the ruling of very fine or closely spaced lines, known as "Test Rulings,"[1] used for testing the resolving and defining power of Microscope objectives. Rulings for this purpose, known as Nobert's Test Plates, were first made by Herr Nobert with the aid of a machine the design of which remained a carefully guarded secret until his death. On this machine he ruled his celebrated Diffraction Gratings, which were the first of their kind available for spectroscopic work.

Several papers,[2] descriptive and critical, referring to the author's earlier work, will serve to show that this fresh undertaking—the construction of a machine for ruling Diffraction Gratings—though far more difficult than anything of the kind previously undertaken by him, had at least a reasonable prospect of being successful, provided health permitted and suitable mechanical facilities were available.

For a time progress was somewhat slow, owing to lack of essential appliances and the very limited time available for so great an undertaking. Both these drawbacks were, however, largely overcome—mainly by an extension of the time available for construc-

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1 "The Microscope," Naegeli and Schwendener, 1889. Translation.

2 "A Wave-length Comparator for Standards of Length," by A. E. H. Tutton, M.A., D.Sc., F.R.S. Phil. Trans. Royal Soc. of London (Series A), vol. 210, pp. 1-34. "On the Measurement of Grayson's Ten-band Plate," by A. A. Eliot Merlin, Journ. R. Micro. Soc., 1910, pp. 5-8. "On the Measurement of Grayson's New Ten-Band Plate," by A. A. Eliot Merlin, Journ. R. Micro. Soc., 1911, pp. 160-163. "Comparative Micrometic Measurements, by Dr. Marshall D. Ewell, Journ. R. Micro. Soc., 1910, pp. 537-554. Also many "Notes" and "References" to Grayson's Rulings by E. M. Nelson, Esq., Journ. R. Micro. Soc., earlier vols.

tional work upon the machine, and also partly in that the undertaking was later recognised as a piece of "Research Work" under the regulations governing University Research Scholarships. The latter adjustment served to bring the work directly under the notice and control of the Professor of Physics, Dr. T. R. Lyle, F.R.S., to whom it was arranged that I should report from time to time. This served to make available additional mechanical facilities, and led to a transference of my services and work to the Department of Physics.

Preliminary Outline of the Design of the Machine.

It is desirable, before describing the more important parts of the machine, to outline its essential features. A fuller description of certain parts is also desirable, as published descriptions of similar machines frequently lack constructional details.

Even Professor Rowland's article, on the grinding of a precision screw, omits reference to important working details; while similar omissions occur in the published description of his ruling machine, issued at a much later date. Thus one frequently fails to find the information sorely needed when entering upon a similar undertaking. The omission of information, with respect to the working routine of these undertakings, may frequently mean the difference between success and failure, or, in any case, great lose of time and labour on the part of those who attempt similar work. Occasionally, even negative experiences are not without value, and are worth recording.

In the following preliminary description of the completed machine, reference to the plates and photographs, particularly Plates VI. to XVII., will be advantageous. For example, Plate VI. is a plan of the complete Engine drawn to scale. The various parts are numbered, and their general purpose and relationships are indicated in the descriptive index.

The bed of the machine, marked A, of cast iron, is a hollow rectangular oblong box, with several internal cross webs for increasing its rigidity. Plate VII., an end view photograph of the machine, shows the external outline of the bed. Externally, the bed has been accurately machined throughout; the top surface and one edge have also been ground true. This form of bed is very rigid in proportion to its mass, and is, moreover, not unwieldy to handle or complicated in outline; its weight, apart from any attachments, is under 70 lbs.

Attached to the outer faces of this simple form of bed are all the essential working parts of the machine, other than the driving mechanism, which is independent of the bed, apart from the necessary attachment to its base. This relationship is shown in Plate VII.

On the right hand half of the upper surface of the bed is the screw (1) with its supports (8), or capped bearings, which are bolted directly to the bed. The screw carries and operates the nut only, and is therefore practically free from any stress or strain other than what is due to a direct axial pull. The connection of the screw with the travelling carriage, supporting the plate to be ruled, is made through two steel bars (19), one on the right hand and the other on the left of the screw, and both parallel with it. These rods are screwed into a horizontally swivelling steel ring, surrounding the outer casing of the nut, and are rendered slightly flexible in a vertical plane by grinding them partly through near the point of attachment to the ring. The nut is therefore relieved from any stress other than the weight of the two rods and ring. The other ends of these rods are joined to a crossbar, and the latter to the carriage, through the agency of parts Nos. 18, 20 and 21, details of which will be found in the index to Plate VI.

The "pitch" of the screw is approximately 20 threads to the inch, or more exactly, 20 threads = .9997 in. at 62°F., and as it may carry one or other of two interchangeable and accurately cut ratchet heads with 360 and 540 teeth respectively, operated by double pawls, its ruling range varies from 20,000 lines per inch down, in to approximately 7200 lines per inch. The position of the ratchet heads, and mode of their attachment to the screw, is shown on the plan and index of the related parts.

The travelling steel nut is 3 inches long, and is lined with a special alloy, related to a bearing metal, in which the threads are cut. After cutting the threads, the nut was ground with oil only, under pressure, to a bearing fit upon a duplicate screw of identical pitch and thread form, and finally upon the permanent screw itself, thus ensuring a true bearing fit throughout. The steel casing of the nut is surrounded by an outer ring of steel, in which, in addition to the rods already described, is screwed a round steel lever (4), the further end of which carries a short revolving bar with hardened bearing surfaces sliding upon an optically true guide bar (13). This bar is adjustible with respect to its parallelism in relation to the screw axis, and can be used, if desired, for slight correction of the pitch of the screw. This last adjustment is effected by means of two micrometer screws (15) seen in Plate VIII. Any elevation of the bar due to a reversed action of the screw and ratchet is obviated by a weight serving as a counterpoise and an upper guide bar (16). The nut has a clear run of nearly 7 inches upon the screw; this range of motion therefore represents the ruling capacity of the engine.

The thrust block (17) with its sapphire bearing face and several adjustments (7 and 7a), are important parts of the machine, which call for great precision in setting, which will be the subject of special mention later. The position of the thrust block is almost exactly central upon the bed of the machine. Hence, it is favourably situated with respect to any expansion of the bed due to temperature changes. The effect upon the ruling of such changes appears to be very slight, as seems to be proved by careful inspection of a 40 hours' ruling, during the progress of which temperature fluctuations amounting to 3°C. were recorded, but appeared to have produced no discoverable change in the regularity of the ruling.

The travelling carriage, which supports the plates while they are being ruled, is advanced by a central axial pull, directly in line with the screw axis, through the agency of the two rods already described, which serve to connect up the ruling carriage with the nut. The advantage of having screw, nut and ruling table joined together in a direct axial line is obvious, and, so far as I am aware, is an arrangement which has not hitherto been adopted in existing ruling engines.

The ruling table itself is simple, being merely a square plate of steel fitted with a detachable, circular graduated revolving supertable for supporting any rulings, or plates for such, requiring angular adjustment. The lower plate, serving as the base, is 6 inches square and $\frac{3}{8}$ in. thick. It slides, by means of semi-circular grooved supports, attached to its under surface, along two heavy circular rods of steel very accurately ground and polished, and resting in special supports screwed to the bed. The chief function of these two rods is to act as guides or ways for maintaining the exact alignment of the ruling carriage with the screw. Most of the weight of the ruling plate, and also of any load it may carry, is borne by a separate under carriage rolling with a minimum of friction directly upon the upper surface of the bed.

The frame and supports of the carriage are seen in outline on the plan as 27, 28 and 29. The under frame (27 and 28) supporting the rods upon which the carriage slides to and fro, is best seen in Plate IX. It consists of two identically shaped strong brackets bolted to the bed, one on each side, which serve mainly to support two rectangular steel bars grooved on their upper surfaces, throughout their length, to the exact curvature of the two circular glass rods (29) which are ground perfectly straight and accurately uniform. These rods rest in, or rather float upon, a viscous medium (thick oil or vaseline) within the grooves of the two steel supports. The glass rods can be slightly adjusted to secure parallelism and alignment, by means of the four screws (30 and 31). Such adjustment is very slight, and made with only just sufficient pressure to prevent any longitudinal movement of the bars.

The chief effect of thus supporting the glass rods is the complete suppression of any tremour or vibration during movement of the diamond carriage over their surface. The surfaces themselves are not only ground, but are semi-polished, so that they consist essentially of innumerable minute facets, and when so prepared render the use of any lubricant unnecessary. It was found that the use of any lubricant would vary in its action, frequently introducing a variable load or pull upon the carriage during the progress of a ruling.

The diamond bearing carriage is seen detached in the plan (Plate VI.), and in various other aspects in the series of photographs illustrating the machine. It is a somewhat complicated piece of mechanism. Leaving to a later page its more detailed description, the following outline of its principal parts and movements will serve to make clear its general operation. The plan shows the outline of the carriage as a rectangular framework, which is built up of brass and steel parts (32, 33 and 34) supporting a superframe (35) carrying all the adjustments for raising and lowering those parts which control the movements of the diamond ruling point, situated at 40, during the operation of ruling a line. The chief adjustment in elevation is effected by means of a central screw (36) operating the dovetailed slide near 35. This slide carries all the parts 37-42.

The lower frame comprises the two broad bars (34) immediately over the glass guides (29). These bars are connected together by means of two steel plates (32, 33). The lower faces of the bars form rectangular grooves, and are fitted with boxwood linings adapted to the curvature of the glass rods upon which the frame slides to and fro. This motion is communicated to the carriage from the eccentric drive (52) and transmitted to the frame through the driving rod (44). A second and smaller driving rod, not shown in the plan, lies immediately under 44, and is so adjusted as to move in the same direction, but slightly ahead of 44, thus raising or lowering the ruling point in advance of any movement of the frame by 44.

The sequence of movements in the ruling of a line is as follows:—The diamond is first lowered into contact with the surface of the plate to be ruled. This is effected by the falling of a bell-crank lever due to the withdrawal of the rod underlying 44. The rod (44) then draws the carriage slowly forward, through the interval determined by the position of the crank (53), and the line is completed. The first return movement, due to the revolution of 53, raises the diamond, through the lifting of the bell crank about .02 inch, above the ruled plate before any movement of the carriage on its ways can occur. The moment the diamond is clear the return journey of the carriage commences, and continues to the starting point of the next line; the diamond remaining suspended both during the return journey of the carriage and feed of the ratchet wheel which occur at the same time. The several movements ars so timed and adjusted as to permit the longest stationary interval to be precedent to the lowering of the diamond for each fresh line.

The time occupied in the ruling of a single line may vary from 5 to 10 seconds, according to the length of the line ruled, and degree of accuracy required. The slowest rate named, calls for some check upon the descent of the diamond point at the start of each fresh line. An unchecked fall would speedily ruin the delicate cutting edge of any diamond suited to this work, hence its fall has to be so graduated as to avoid any sort of shock or blow. This is effected through the agency of three plungers and dash cells, the latter containing a fairly thick oil. The plungers are situated at 42 and 42a. The lines are also, by this means, freed from the effects of undulatory vibration of the diamond in a vertical plane.

This brief reference to the action and control of the diamond during the cutting of a series of lines might properly lead to a description of the form of diamond, best suited to this work, at this stage. A careful study of the cutting action of a diamond for ruling lines of such extreme tenuity and perfection as are required for diffraction gratings, is of the very first importance. The amount of work required of a diamond in the cutting of even a medium-sized grating is equal to the cutitng of a single continuous line of over a mile in length. This line, or rather series of lines, must throughout be without appreciable change in depth, width, or in its capacity to reflect light. These and other considerations, which are particularly well described by Professor Michelson,[1] afford some idea of the amount of care required in the selection, testing and adjustment of a ruling diamond. As it is our intention to refer in detail to the selection, preparation and general manipulation of a diamond suitable for ruling fine lines, and to illustrate its action under varying conditions, further reference is, for the present, postponed.

Driving Mechanism.

This includes chiefly the driving Engine, also such parts of the machine as are essential for the transmission of motion to those of its features just described. Respecting the motive power: while the total energy required may be very small—say below $\frac{1}{8}$ H.P., it must be continuously and uniformly exerted over long periods. Any stoppage, no matter for how short a time, would be ruinous in its effect. Even a slowing down of the engine, such as would cause a variation in speed of more than a few per cent., would be highly detrimental.

It appears to have been the usual practice to select some type of water or electric motor for operating the most recently constructed ruling engines. Electric power seems to have been availed of by Rowland, and also for driving the Blytheswood machine, now at the National Physical Laboratory.

No doubt the electrical drive may be advantageous when suitable storage batteries are exclusively available. As access to such batteries was not at my command it was decided to try the next most suitable driving-power obtainable, viz., a small hot-air Engine. Several preliminary trials with this type of motor were very promising, and as the total energy required was found to be very small, not more than 1-40 H.P., an engine of that nominal capacity proved to be fully adequate for all requirements.

This motor has now been in almost continuous use for about three years and has never once failed. It runs, with a minimum of attention, for comparatively long intervals. And as it gives off but little waste heat, and is free from vibration and noise, it can be placed in a room adjoining that of the ruling engine. It has, in fact, proved an almost ideal engine for accomplishing a somewhat difficult task.

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1 See "Nature." Jan. 11th, 1912.

The method of its adaptation to its work is as follows:—It is set up in an outer room adjacent to the small specially constructed room in which the ruling machine is housed. When at work the engine is regulated to run at about 250 revs. per minute. This speed is reduced to about one-fourth by means of leather bands and aluminium speed reducing pulleys. Motion is given to the machine by a cord passing directly from the reduced drive, through a narrow slot in the wall of the machine house, to the driving wheel (60) on the main shaft (57) of the ruling machine. The shaft (57) is supported on a portion of an underframe which comprises three parts indicated on the plan as B, C and D. It will be noted that plate D rests upon and is bolted to B and C, which in turn are attached, by means of angle brackets, to the lower projecting flange of the machine bed. This construction has the merit of greatly reducing the weight of the whole machine and yet secures sufficient rigidity.

Describing in order the parts of the machine supported on D, B and C; D carries on its upper surface two stout iron pillars, one near each end, which support the driving shaft (57), a circular rod of steel about 28 inches long, resting on bearings (55) with adjustable collars (56). Near its right-hand end are two cam collars (58 and 59). These are constructed so as to slide along the shaft, and are recessed on their inner faces. Within the recess is placed a cam, provided with means for lateral displacement as required; it lies immediately under its lubricating pad and spring (62). A slotted, under cut, circular brass disc (54) is screwed to the opposite end of the main shaft, and provides for the eccentric adjustment of the crank bar head (53). The range, up to three inches, of this adjustment governs the length of the lines. On inspection of Plates VII., VIII. and X. will serve better than further verbal description to make clear the construction and relations of the parts just named.

The second plate, B, carries a single substantial iron pillar (64) which forms the main support and fulcrum of the steel lever bar (61). One end of the lever passes under the cam on 57, and is pivoted at 63, with provision for adjustment and alignment in relation to both cam and ratchet wheel. The ratchet end of the lever is fitted with a small and carefully made frame which supports and controls the pawl or pawls engaging the ratchet teeth (9). The pawls are fitted with the utmost care and are controlled through the agency of the several parts of the frame (66 to 69). Just below the frame carrying the pawls is a support provided with screw adjustment and lock nut for regulating its height. The top surface of the pillar is hardened and polished, and serves as an arrest for a hardened spherical projection extending from the main lever immediately under the pawls. The arresting pillar and its adjustments are attached to a separate base plate (11) extending out from the base of the main bed of the machine to which it is bolted. The two screws, the heads of which are shown on 11, have no relation to B; they, however, prevent any flexure of 11, due to the weight of the lever and counterpoise (65) descending upon it. It is, of course, important that all movements affecting the ruling be regulated to avoid the sudden arrest of any movement affecting the operation of the diamond point; hence the provision throughout the machine of a variety of parts necessary to its protection. Reference to Plates VII., VIII. and X. will serve to supplement the brief description of the features indicated.

Passing to base plate C. A glance at the plan will show that it is complementary to B in its relation to D and the main bed of the machine, to both of which it is similarly attached. Plate VII. shows its position, and indicates in perspective its purpose. It forms the base of a rigid pillar, of cast iron, supporting a frame which carries the two steel rods (50). These rods, both of which are accurately ground, mainly serve as guides to a small platform of steel, through the agency of which the eccentric swing or throw of the crank rod (52) is converted into a steady, even horizontal "to and fro" motion, as free as possible from any kind of constraint. This movement can be communicated to the ruling carriage as required. The transmission of a smooth and even motion is due primarily to the attachment of the connecting rod (52) to a rotating crosshead placed between the two guides (50) immediately below the lower plate or base of 49; and in part to the carefully fitted sleeves sliding on 50. To the upper surface of platform 48, are secured the various adjustments needed to effect and control the motions of the ruling carriage, the chief of these being the centre block (47), which is rigidly screwed to the surface of 48. The communication rod (44) passes through the centre of 47, one end screwing into a rocking bar on the ruling carriage, the other resting partly in a guide frame (45) and partly in block 47. On opposite sides of the latter (47) are small sleeves or clamps fitted with binding screws; these, if free or clamped at a sufficient distance from 47, will permit 44, on which they travel, to slide freely through 47 without communicating any motion of the main driving rod (52) to the ruling carriage. When, however, the clamping blocks are brought closer to 47 and secured, the free motion of 44 is restricted to a precise interval, which may vary from 0.01 in. to 0.1 in. or more, as desired; any further motion exceeding the interval to which the setting has been adjusted is of course communicated to the carriage. The purpose served by this preliminary movement of 47, which is not communicated to 44 or the ruling carriage, is to permit of the lowering and raising of the ruling diamond at the beginning or end of each line. This is effected by means of a second rod which passes through 47, and may be clamped therein at any convenient point in relation to the end, which pushed against a small lever. This lever lowers the diamond point before the ruling of a line and raises it from the plate on the return traverse as already explained. The location of this rod is not seen on the plan, as it lies immediately under 44 and parallel with it.

As brief reference has already been made to the operation of the diamond when ruling lines, further allusion to the subject may be deferred until the matter is dealt with in detail.

The foregoing brief outline of the chief mechanical features and operation of the machine and ruling mechanism may fittingly close with a short description of its earliest trial runs, and the subsequent housing, etc., after which a more detailed account of certain of the methods adopted in the construction of its more important parts will be entered upon.

The Housing of the Ruling Engine, etc.

The provision of suitable accommodation for a machine for such exacting requirements as are involved in the ruling of a diffraction grating is of some moment, especially when it is borne in mind that such a machine has to run for long periods ranging from 20 to 200 hours at a stretch. During such intervals there must be no very appreciable change in temperature of the air immediately surrounding the machine, that is, no change exceeding two or three tenths of a degree. Further, during the ruling of a grating the machine must not be subjected to vibrations, such as might arise from the proximity of trains, trams, or any heavy vehicular traffic; nor yet to shocks or tremors due to the operation of other machinery in the same building or immediate neighbourhood. Thus the possibilities to be provided for or against are by no means easily met.

On the completion of the machine, it was not found possible for some considerable time to house and use it under conditions favourable to a satisfactory trial of its capabilities. Hence perforce it remained in an ordinary dwelling-house situated not far from a railway, but otherwise fairly free from serious disturbing influences, other than those inseparable from such a location.

Seeing that for a time no other alternative offered, it was decided to make the best of the available accommodation. The machine was set up on a brick pier, erected below the floor of a small room used as a study, etc., in which the temperature conditions were fairly even. In the main, the results from a series of trials justified the experiment. Certainly, defects of various kinds were apparent, and for some of these remedies were devised, this being one of the objects for which the trial was undertaken. But the principal result of the experiment served to prove that it was possible, in the intervals between the somewhat extreme fluctuations of temperature to which our summer climate is liable, to rule fair gratings, even under adverse conditions.

Subsequently a large sub-basement room, having very thick outer walls, situated under the main Library of the University, and sufficiently remote from disturbing influences akin to those named, was partitioned off into two smaller rooms. One of these is used for spectroscopic examination and work, while within the adjacent room a still smaller room has been constructed especially for the accommodation of the ruling machine. The latter room has double walls, the intervening space being filled with non-conducting material, consequently a very uniform temperature can be maintained for a considerable period, the variations being mainly of a seasonal character. Within this small room, a foundation of dry sand, enclosed within cemented brickwork, has been laid down below the floor level. A heavy stone slab, resting upon the sand, serves to support a brick pier capped with a thick slate bench insulated from the brickwork with rubber pads. The upper surface of the slate is ground smooth and true, and carries the machine and driving gear, other than the engine; the whole being enclosed within a carefully constructed case, consisting mainly of heavy glass sashes, affording ready access to every part of the apparatus. The driving motor is placed outside the machine house, and does not affect its temperature. As the gas consumption of the motor is under one cubic foot per hour, any heat from this source is easily conveyed from the room.

It will be perceived from the foregoing that the provision respecting insulation, isolation, general stability and comparative freedom from temperature variations, combined with easy accessibility, leaves little of importance unprovided for. Naturally, the result of favourable conditions in the housing and surroundings of the machine was a pronounced improvement in the quality of the gratings ruled, even apart from further mechanical improvements resulting from a more extended acquaintance with the working of the machine.

This general account of the more important mechanical features of the Ruling Engine will, it is hoped, convey a fair idea of its structural divergences from other machines designed for ruling gratings; that is, so far as descriptions of such machines have been published. Two such descriptions, more or less complete, have recently appeared, viz., that of the Blytheswood machine, now at the National Physical Laboratory, and a partial account of a new machine designed by Professor Michelson, of the Chicago University. Descriptions of Ruling Engines of earlier design, as for example those of Nobert, Rutherford, and Rowland, have been published. With perhaps the exception of the Blytheswood Engine, few of the descriptions convey to the reader any very detailed or important information concerning the actual construction of a machine of this character. Therefore, as much of the work entailed differs from ordinary instrument work and involves an intimate appreciation of minute values, it may be useful to give some account of the actual work involved in constructing special parts of the machine. The methods adopted were largely due to unavoidable limitations, and better results might have been attained by other means.

This record is primarily the fulfilment of a definite obligation to the University whose generosity has made the building of a machine possible of accomplishment. That the information concerning its construction, which is here given, may be of service to others who may be engaged on similar or related work, affords the possibility of additional usefulness.

In conformity with the foregoing, the following special parts of the machine appear to merit more detailed attention, namely :—

1. *The Screw.*
2. *The Ratchet Wheel.*
3. *The Thrust Plate.*
4. *The Ruling Diamond.*

1.—The Screw.

Embracing :—

1. Cutting the screw thread and (i.) the grinding nut.
2. Process of grinding the screw, including :—
   - (i.) Preliminary separation of Emery or other abrasives.
   - (ii.) Method of Refining crudely separated abrasives.
   - (iii.) Preliminary grinding of the screw by hand.
   - (iv.) Grinding with fine abrasives and semi-automatic control.
   - (v.) Mode of operating the mechanical grinder.
3. Method of testing the screw and its bearings during final correction and adjustment.

I.—*Cutting the Screw Thread.*

The method of cutting the screw thread hereunder described differed but little from that adopted by Rowland and others, but the process of grinding it varied in important particulars. The Rowland screw appears to have been ground between the regular lathe centres by means of a specially constructed brass nut, described in the article on "Screws" in the Encyclopaedia Britannica. The process of grinding followed by the writer varied materially, and is described below. With respect, first, to the operation of cutting the thread.

A suitable bar of mild steel was selected and carefully annealed by slow heating and cooling. Its diameter permitted of the removal of several heavy cuts from end to end of its length, after which it was again annealed, accurately centred in the lathe, and turned down to about $\frac{7}{8}$ in. diameter with repeated light cuts. Later experience with other screws has shown that fine grinding may be preferable to turning as a preparation of the surface for threading, as it is not so likely to warp and compress the rod, and leaves its surface more uniform and true.

The cutting of the thread on the prepared bar differed in no wise from the routine usually followed in the cutting of a good thread. The lathe was run slowly with an abundant supply of potash soap solution continually playing on the threading tool. The advance or forward "feed" of the cutting tool should never result in a heavy cut, and as the work proceeds the cuts should be reduced until those finally taken are approximately only .0005 of an inch. It is, however, important that the last cuts taken should be continuous and even throughout the threaded length of the bar, even though this should involve a slightly heavier cut than that just named. Also it is material that the over-all threaded length of the bar should exceed by several inches the portion it is proposed to use in the finished screw.

The thread " pitch " and " angle " should be appropriate to the work for which the screw is designed. The pitch value of the screw here described is 20 threads to the inch, a value convenient for subdivision, and the thread angle 50°, permitting of a somewhat deeper thread than the usual Whitworth standard; both " crown " and " root " of the thread, previous to grinding, remained as left from the threading tool. The greatest care was taken so that the intersections of the thread walls with any plane through the axis of the screw should be straight lines—a precaution applying equally to the counterpart threads within the nut. Should the work for which a screw is being cut justify the expenditure of the time involved, it will pay to cut several screws at the outset, selecting two of the best for final grinding.

(i.).—*The grinding nut.*—For grinding his screw, Rowland, according to the Encyclopaedia article, appears to have made use of a brass nut constructed externally so as to taper from the centre towards each end, and split longitudinally into four equal segments which could be fitted to the screw and held in position by means of sliding sleeves or collars adapted to the tapered ends of the nut. The opposing sleeves were connected with bolts and nuts, and could thus be drawn together as the work of grinding proceeded.

Some objection may be taken to the use of this form of nut for grinding a precision screw for the following reasons:—(1) The use of a brass nut upon a steel screw has the disadvantage due to the wide difference in the coefficients of expansion of the two metals, as some heating will take place in the process of grinding. To avoid heating, the work of grinding must either proceed very slowly or else be conducted under water or oil, which entails very serious disadvantages. Hence any gain from the use of brass, due to its superior action with abrasives upon a harder metal, is lost. (2) The division of a grinding nut into four segments appears to be faulty, in that it is possible for one or more sections to move slightly in relation to the others providing, as is almost sure to be the case, there are periodic or other irregularities in the screw. While the method of tightening up the segments is likely to produce uneven pressure, so that one or more sections of the nut may do more than their share of grinding, even though the general trend of the pressure applied may be in the direction of uniformity of action. Thus any advantage derived from increased surface action, resulting from the use of a segmented nut, may be somewhat discounted by unequal pressure.

The foregoing and one or two minor considerations led up to the decision to employ a continuous steel nut of sufficient thickness and rigidity to resist any variations in pressure which were likely to be used upon it. This nut was cut, bored and threaded up to a length of about 10 inches, which was nearly equal to the length proposed for the finished screw when in use.

This long nut was threaded on the lathe used for cutting the thread of the screw, with a threading tool and such other conditions and precautions as would result in the closest correspondence between the two threads.

The outer wall of the finished nut was slotted through on one side and partly so on its inner opposite side. The two halves of the nut could thus be drawn or rather forced together on the application of moderate external pressure at suitable points. To effect this pressure the nut was encircled with three strong metal rings fitted with set screws bearing directly on its opposite sides. As the rings, under pressure, were slightly elastic or yielding the pressure exerted by them was free from any rigidity likely to lead to seizure between the respective surfaces of nut and screw. Fig. 2, Plate XI. illustrates several of these features.

II.—*Process of Grinding the Screw.*

As may readily be supposed, success in grinding an accurate screw is so intimately related to the abrasive used, that some account of the properties and preparation of those commonly employed is desirable before treating of the method of their application.

The following three well-known substances, in the form of abrasive powders, viz.: Carborundum, Alundum and Emery were used, at least to some extent, experimentally in grinding the screws. As each of these abrasives possesses qualities and structural peculiarities of its own, some explanation of the method of separating or grading, with respect to size and uniformity of grain, is essential to an appreciation of their efficiency.

With respect to their nature and qualities:—

Carborundum, whilst by far the hardest of the three substances, is also the most brittle and the least suited for application to such a comparatively soft metal as mild steel in its annealed state, as minute particles become imbedded in its surface. Commercially obtainable in the form of very finely divided powders, microscopical examination of even the finest reveals the presence of numerous acutely angular, and frequently needle-like particles, very difficult to separate to a uniform shape and size of grain. Thus, though rapid in action as a cutting and grinding agent, Carborundum is liable to score and scratch finished surfaces to an extent disproportionate to the average grading of the powder used. Moreover, the grades not infrequently contain a considerable amount of graphite, which is apt to soil and obscure the surfaces being operated on.

Alundum, when obtained in the form of an abrasive powder, is usually white and clean. Though not so hard as carborundum, it is tougher and somewhat less variable as to the shape of its particles. It may readily be separated into the finest grades, which are clean to work with and effective in action.

Emery, as an abrasive, is rounder and more uniform of grain than either carborundum or alundum, compared with which it is not so hard as either, but possesses the quality of toughness to a greater degree. Owing to its fairly high specific gravity it can readily be separated into a very effective series of finely divided powders suited for use upon mild steel, on which the finer grades leave a uniformly smooth or even polished surface.

As, practically, the process for the separation of any of these abrasives is the same, we may describe that used for separating emery as typical, the details being as follow :—

(i.).—*The preliminary separation of Emery or other abrasives.*— In connection with other work, considerable quantities of separated abrasives were required; the experience gained in their separation was availed of in the selection and preparation of the materials required for grinding the screws; the process being, in respect to the separation of emery, as follows :—

As commercial flour emery contains a relatively large amount of coarse material, that is of grains over .001 inch in diameter, down to small grains unsuited for abrasive work of the kind here described, the work of separation is best accomplished by first subjecting the crude powder to a preliminary treatment. The quantity dealt with, it must be understood, was proportioned to the work for which this particular separation was required. A third of this amount would, of course, be ample for the supply of material for grinding several screws.

A quantity (usually about 3 lbs.) of the finest flour emery was tied up in a piece of linen or canvas of moderately open texture and kneaded under water, preferably warm, in any convenient vessel until the whole of it had been washed out. This treatment ensures a thorough wetting of all the emery and prevents it from floating upon the surface of the water used in the later stages of its separation. The water and emery were next thoroughly agitated and passed through a fine sieve of wire or milling silk to separate out any coarse grains of emery or other material present. For this and the subsequent operations, four or five large tins holding about four gallons each (empty kerosene or petrol tins do very well) are required. Having washed the whole of the material through a suitable sieve, more water may be poured in to nearly fill up the tin, to which is added a few c.c. of a 20 per cent. solution of Tannic acid, which acts as a deflocculent if not in excess. (Repeated additions of this solution are made with each fresh supply of water as the separation process is continued). After a thorough stirring, allow the vessel to stand for ten minutes and then decant with care the upper three-fourths of the water, carrying in suspension the finer emery, into another tin. This process should be repeated several times, with fresh supplies of water, until it is seen that most of the finer material has been decanted from the original sample. The sediment remaining will consist mainly of the coarsest grains present in the original samples, and may be set aside to settle in a smaller vessel or beaker and afterwards dried off. We have next to deal with some 8 or 10 gallons or more of water, containing finer emery than will fall through the depth of water each vessel contains—say 8 to 10 inches in 10 minutes; but will settle in say 20 minutes. Hence we proceed with the separation of this finer material much in the same way as we dealt with that which came down in 10 minutes, providing sufficient vessels are available; if not, allow the vessels containing it to stand and settle for about 80 minutes, when the upper portion of the water in each, in which there will remain in suspension only fine material of little or no abrasive value upon a screw, may be poured away as close to, but without disturbing the sediment, as possible. The several sediments having been transferred to one vessel, with additional water as required, and well stirred, are allowed to stand for 20 minutes, when the upper portion of the water containing still finer emery is poured off, as before, into other tins. The addition of fresh supplies of water and time for settlement (20 minutes) being continued, so as to secure as much of the fine material as possible. The sediment remaining, consisting mainly of material which settles in 20 minutes, may be put aside for use or further treatment. We may next deal in the same way with the still finer emery contained in the water decanted off from the 20 minutes sediment. Much of this will require a still longer time—say 40 minutes—in which to settle and so obtain a further and yet finer grade of emery. The addition of more water and decantation, etc., being continued, as in previous grades, the time interval only being extended to 40 minutes with a corresponding increase in care in the several operations. In order to obtain a small supply of the finest effective material present, it will be necessary to carry on the separation process with a 60-minute interval for settlement, the sediment from which will be small in bulk but proportionately valuable for the final abrasive work.

The process of separating abrasives thus outlined is both slow and tedious, and may extend over one or two days. As, however, reliable separations are absolutely necessary if good results are desired, it pays to go to considerable trouble to obtain them.

It is, of course, not necessary for the purpose of grinding one or two screws only to undertake the separation of so large a quantity of material as that above named; but it is essential that an effectual grading of whatever abrasive it is proposed to use be made; and also that the process of separation should be carried to an even greater degree of refinement than is possible with the rough and ready method above outlined. This process only afforded a series of crude powders in which there is considerable variation in the size of the grains.

To secure greater uniformity of grain, and greater smoothness in working, than is possible with any of the four sediments or separations just described, the following more exact method of treatment was adopted :—

(ii.).—*Method of Refining crudely separated abrasives.*—Before commencing to grind the screws, we had the good fortune to have at hand a series of carefully separated powders of all the abrasives we have described and used; also some knowledge of their behaviour under varying conditions upon a variety of materials. This experience had, in the main, tended to show that the greater the care bestowed upon the separation of an abrasive, the more efficiently and as a rule more quickly, could a desired result be obtained.

Guided by this knowledge, confirmed by microscopical evidence from the examination of a variety of powders, it was decided to carry on the process of separation of the three finest grades of emery, obtained by the decantation method of separation, to a greater degree of refinement, the method adopted being essentially as follows :—

A circular upright glass jar, about 10 inches high by 5 inches wide, was roughly graduated into one-inch spaces. With this jar, the syphon and attachments shown in Fig. 1, Plate XI., were used. The attachments include a glass tube of about 5 m/m. bore, bent as indicated; the short arm being longer than the depth of the vessel used with it. The longer arm is extended as required with rubber tubing; it must be more than twice the length of the short arm, and retained at a length convenient so as to maintain a constant pressure at the outflow. Various sized jets to control the overflow of the syphon are required. A convenient series of these jets, which are not difficult to make and adjust, should permit of the whole of the water being withdrawn from the container during intervals of about 10, 20, 40 and 60 minutes.

It should be noted that the short arm of the syphon passes through a large circular piece of cork, which acts as a float upon the surface of the water in the graduated container, and also serves to regulate the depth of the intake tube. The bent syphon and its attachments are suspended and counterpoised by means of a cord, pulleys and weight, as shown in the figure, the outfit being completed with overflow receptacles.[1]

Before using this outfit with the particular grade of abrasive it is proposed to refine, the rate of flow from the syphon should first be adjusted. If the required grade is one of 20 minutes, the water level in the container should be lowered one inch in two minutes. Generally it is better that the time should exceed rather than fall short of the interval for which the adjustment is made. Everything being in readiness, the container is filled to the upper graduation mark with thoroughly mixed emery and water and allowed to settle for about $2\frac{1}{2}$ minutes, before the float is lowered upon its surface or the syphon clamp removed. On releasing the latter the water level should fall to within about one inch from the bottom of the container. The inlet tube is prevented from descending too near the surface of any sediment on the bottom of the container by inserting 3 pins or bits of wire tripod-wise into the under surface of the float

1 The overflow vessel must be placed well below the syphon outlet and not as shown in the figure, which was thus drawn for convenience of reduction.

so as to project below the inlet at least one inch. This device will prevent the withdrawal of any coarse sediment from the bottom of the container in case the clamp should not have been replaced in time. After syphoning off to a safe level the clamp is replaced, the tube and float withdrawn and a further supply of untreated sediment and water poured into the container and the syphoning conducted as before, afterwards water only is added and the syphoning continued so long as any considerable proportion of abrasive remains in suspension. The water withdrawn through the syphon carries with it most of the fine material suspended in the container; the bulk of the heavier particles, maintaining their initial advantage in descent during the stated interval, make their way to the bottom of the vessel. By this method of treatment, as will readily be perceived, a much larger proportion of fine material can be withdrawn in a given time, while the regulated discharge ensures a more uniform grading.

Respecting the fine material thus withdrawn, the vessels containing it may be left to settle until the water appears comparatively clear, when it may be poured off and the sediment transferred to an evaporating dish preparatory to drying off. Before drying, the material should be examined under a microscope and the average size of the grains determined, in case it should be neecssary to repeat the separation process, with a slightly longer time interval, in the event of too great a disparity between the size of the various grains.

Much the same mode of procedure as the foregoing applies to each of the crude separations first made, with correspondingly coarser or finer jets and longer or shorter periods for settlement. It must be borne in mind in this connection, that a small quantity of carefully separated abrasive is far more effective and uniform in its action than many times the same quantity imperfectly treated. Hence, though the process of separation may appear tedious, it will prove to be a wise economy to carry it through. Four grades only of any particular abrasive thus treated are all that are really necessary to complete the grinding of a precision screw, providing the thread has already been carefully cut. With a view to present to the reader a graphic representation of the uniformity in size of grain attainable by this mode of separation, a series of photo-micrographs with a magnification of approximately 75 diameters has been prepared and are shown as Plate XII., Figs. 1 to 6. Respecting these photographs it is first necessary to point out that it is extremely difficult to secure uniformity in the distribution of powders so fine in grain as those represented owing to their tendency to clot or segregate; and also that the magnification used was somewhat too high for the coarse-grained samples, and too low for the finer ones. In spite of these drawbacks, the photographs render sufficiently apparent the differences in size and character of the grains. For example, Figs. 1 and 2, Plate XII., illustrating alundum, the grains of which are respectively .0015 in. and .0003 of an inch, are adequate to make clear the difference in grain between the respective sizes. Again, Figs. 3 and 4, representing two examples of carborundum, show clearly the more angular character of the grains as contrasted with alundum, and a coarse emery. The difference between carborundum and emery, with the same sized grain, is less striking but yet appreciable; the emery being the more uniform of the two samples.

Fig. 5, Pl. XII., shows an emery with an average grain of .001 in. diam., the coarsest abrasive used upon the screw, and with the rounded character of grain already referred to. The fine emery shown as Fig. 6 was used mainly for finishing purposes only, acting rather as a polishing agent than as an abrasive, and leaving the screw threads in a semi-polished condition.

Combinations of emery, alundum and carborundum, having the same size of grain, were occasionally used, and proved advantageous in the earlier stages of the grinding process.

Having prepared a series of abrasives, the operation of grinding the screws was entered upon, and may for convenience be divided into two stages, the first of these being the *preliminary rough grinding by hand*, using a relatively coarse abrasive, and the second stage, grinding with fine abrasives and more or less *complete automatic* or *mechanical control.*

(iii.).—*The Preliminary grinding of the screw by hand.*—This operation involved fitting up the lathe with extra long centres so as to permit the grinding nut to travel beyond the threaded part of the screw bars for at least several inches at each end. For this purpose, the screw was revolved slowly, while the nut was held and controlled by hand. The whole of the grinding at this stage was done with one grade of emery only, viz., that described at Fig. 5, Pl. XII., having an average grain diameter of .001 inch. This emery, mixed with oil, was fed into the nut along the slot, the ring clamps being released to permit of its introduction and even distribution. Pressure upon the nut was applied very gradually at this stage, and the grinding continued for ten minutes, when the nut was reversed and a fresh supply of emery fed in. Thus the work of grinding went on under moderate pressure, regular reversal of the screw and fresh supplies of emery and oil.

As already mentioned, two screws were ground with the same nut, which necessitated a change from one to the other about every half-hour. No very great precautions were taken to maintain uniformity of temperature during these early operations, nor did this appear to be necessary, seeing that each grinding operation lasted only for a comparatively short time. The grinding, as described above, covered about 12 hours' actual work. which was distributed over several days. During this preliminary grinding, attention was mainly given to the supply of abrasive and oil, which was carefully and uniformly distributed over the full length of both screw and grinding nut at frequent intervals, the precaution being taken not to exhaust its action before renewal. Care was taken to apply only moderate and uniform pressure upon the nut, which was regularly reversed and changed with respect to the screw, and supported so as to avoid flexure. The precaution to wash out the nut with kerosene, and clean off the screw with cotton waste about every three hours, was not overlooked.

When inspection with a magnifying lens indicated that the whole of the threads appeared to have been ground to a uniform condition, as shown by the disappearance of any tool markings, it became necessary to devise some simple form of test, capable of revealing any very marked periodicity, and general condition of the screw throughout its entire length as regards the crowns, roots and angles of the threads and their bearing surfaces. For the rapid inspection of the screw with respect to these features, a small examination bench was constructed as follows:—A platform of thick plate glass, rather longer than the screws and three inches wide, was supported at each end, at a height of about three inches above a wooden base. Screwed to this base were two guides, also of wood, adjusted so as to permit the square base of a microscope stand to slide between them from end to end of the platform. During an examination the screws rested upon the glass platform with the threads interlocked and adjusted parallel to the travel of the microscope along the main base. With the aid of a long strip of white card, placed below the platform supporting the screws and adjusted to an angle suited to the direction of the incident light, ample illumination for a magnification of 20 diameters or more was obtained. The two screws rested upon supports slightly inclined to each other, hence they could be revolved, reversed, interlocked, or interchanged without disturbing their adjustment in relation to the travelling microscope. This comparatively simple and easily constructed bit of apparatus proved quite satisfactory for examining the condition of the two screws, not only during the preliminary grinding stage, but up to the final mounting of one of them in the completed engine, it was only superseded, after a number of gratings had been ruled, by a more rigorous method of testing described on a later page.

(iv.).—*Grinding with fine abrasives and semi-automatic control.* —A thorough examination of the two screws under the microscope, with the aid of the apparatus above described, tended to show that it was not desirable to continue grinding without appliances which would permit of a more precise control of the operations involved. Hence the following method for attaining variable speed control, freedom from stress, other than that due to a uniform tortional resistance, and the maintenance of a more uniform temperature, was adopted. An attempt to eliminate temperature changes resulting from friction by means of a stream of running water or oil, surrounding nut and screw, proved unsatisfactory and was abandoned at an early stage in favour of a reduction of speed and pressure. An inspection of Fig. 2, Plate XI., will make clear the following brief description of the appartus used. Fig. 2 is a photograph of the complete mechanism used at this stage, and in all subsequent grinding operations. It comprised a strong wooden platform or plank securely bracketed to the wall of the workshop in a position conveniently near the overhead driving gear of the lathe which furnished the operating power. A strong flanged accurately bored metal socket about 6 in. long was screwed to the upper surface of the platform. Through this a mandril passed, carrying on its upper end interchangeable driving wheels, and on its opposite end below the platform a small chuck fitted with universal movement. This chuck supports a steel rod about 15 in. long, to the lower end of which the screw is attached, the latter being thus provided with a free conical pendular motion of about 20° amplitude; two jockey pulleys for transposing the vertical travel of the driving band, and a reversing lever (not shown) complete the driving mechanism. In Fig. 2, Pl. XI. the screw and nut are seen in position, exactly as in the operation of grinding. The details of the nut include its two surrounding rings and clamping screws, previously described; also a centrally situated steel ring carrying reversible suspension hooks and two projecting arms which bear against polished steel rods extending from platform to floor, and serving as guides to direct and steady the nut in its ascent or descent, and also prevent its rotation. As will be seen, the grinding nut is counterpoised by weights; the pulleys and cords travelling with a minimum of friction. The rotary motion of the screw was made variable, ranging from 120 down to 40 revolutions per minute, the latter being the slowest rate of speed used. It is hardly necessary to state the fitting up of these simple appliances was carried out with care, the rotation of the spindle, particularly, being made as true as possible, and free from vibration or shock, especially at the moment of reversal, which was always made with a reduction in speed.

(v.).—*Mode of operating the Mechanical Grinder.*—In operation, the mechanical device just described presented no great difficulty. Once the screw had been adjusted to run smoothly, the nut was screwed into position, the clamps meanwhile being released, and oil, without any abrasive, applied as a lubricant, and the machine was ready for a trial run. In order to avoid the possibility of seizure between screw and nut, the latter was controlled by hand for a time, the projecting sleeves being withdrawn from the central ring, leaving the screw free to revolve while the machine was being stopped. These precautions were no longer necessary once the machine was found to run smoothly, and some experience of its working had been gained. It will be understood that grinding with a power-driven machine differs materially from the same work controlled by hand, and is to a greater extent dependent upon the sense of touch and hearing; these being the chief means of estimating and controlling the nature and extent of the work being done.

The mode of applying abrasive is now of considerable importance, and can be controlled and varied so as to materially modify its effect upon the screw. Ordinarily, when applying a fresh grade of abrasive or re-commencing operations after cleaning nut and screw, it was usual to release all clamping pressure and run off the nut below the screw; the latter was then coated with a thin even film or layer of abrasive mixed with oil—and in this connection it may be remarked that a light mineral oil and olive oil, in equal parts, was later used. This combination was found to possess certain advantages over either of its components used alone. Thin mineral oil was found to dry up rather rapidly and was more liable to produce an increase of temperature in consequence, while olive oil alone proved somewhat too viscous, especially with the finer abrasives.

The screw having been evenly coated with abrasive, the nut is run into a central position upon it, and pressure brought to bear, evenly and slowly, rotating the nut by hand while this is being done. In order to ensure a positive and uniform pressure the clamping screws are advanced alternately until they are felt to grip gently, and are then slightly relaxed. We thus ensure a condition for both nut and screw in which it will be safe to run for a short time. During all starting operations, close attention is paid to the machine, until we are assured the running is satisfactory. Providing the pressure on both rings is properly proportioned, and the condition of the screw is known to be of a fairly uniform character, it is quite safe to run at a speed of 120 revolutions per minute, with an abrasive (alundum) of a uniform average diameter of grain of about .0007 inch. This was found to be a suitable grade to follow that of emery used in the hand grinding already described. A mixture of equal parts of alundum and carborundum was, however, later substituted for alundum alone. Having allowed the nut to travel up and down the screw a few times, the former was run off and reversed, and re-engaged by hand over several threads; the latter being a precautionary measure *never omitted*, otherwise damage might result to either nut or screw or both. The nut having attained a central position once more, some readjustment of pressure may be required. This is effected exactly as before, and when found uniform, the work of grinding should proceed for the same time interval as before reversal. After the lapse of this interval, it will probably be found that the abrasive and oil tend to work away from the centre to opposite ends of both screw nut, and if attention were not given to correct this tendency, it would eventually lead to a slight tapering of the screw from its centre towards each end, and particularly to that end which was lowest during grinding. At a later stage, it was found possible to counteract this tendency, partly by varying the distribution of the abrasive, and partly by extending or restricting, as the case required, the travel of the nut upon the screw. It might readily be supposed that the central portion of the screw would be more rapidly ground than the ends, providing the nut does not travel over the full length of the screw after each reversal—to permit which is not usual or wise. As a rule it was found best to reverse the motion of the nut when from two-thirds to three-fourths of the screw length had been traversed, i.e., about one-third of the nut should generally remain engaged upon the screw.

Regarding the re-distribution of the abrasive as the grinding proceeded; this was usually done by using a flat camel's hair lacquering brush to collect any excess oil and abrasive and transfer it back to the central and upper portion of the screw, in advance of the travelling nut in either direction; whilst additional supplies of oil and abrasive were carefully inserted into the slotted nut by means of a piece of leather cemented to a strip of aluminium or zinc. This proved both safe and satisfactory, as only the edge of the leather, charged with abrasive, came into contact with the revolving threads. After about three hours of carefully controlled work, it was customary to run the nut off the screw, detach it and thoroughly wash out the threads with kerosene, with the aid of a stiff tube brush. The screw also would be dismounted and similarly treated. In this, and all other operations involving reversal or detachment of the nut, attention was constantly required to avoid the accidental introduction of dust, hairs, or any kind of fibrous material, which might cause the nut to jamb or seize. Attention was also directed to any temperature change by inserting a sensitive thermometer into the nut whenever the latter was detached; three degrees being the limit of variation at this stage of the work. After cleaning the nut and screw, it was usual to make a fresh examination of the latter under the microscope; its condition, in respect to the action of the abrasive upon it, being noted. At the same time the diameter of the screw was measured with a micrometer; the measurements obtained providing data for adjusting the travel of the nut upon it, and to some extent, for any increase or decrease in pressure; though, as a rule, the latter was more accurately controlled, during the operation of grinding, by the sense of touch. No precise record of the time taken to reduce the surface of the threads to a uniformly smooth condition was made at this stage, but for this particular grade of abrasive, it was not less than 40 hours; the work being distributed over a fortnight or more. Inspection then showed a decided improvement in the condition and appearance of the screws. The scoring due to the coarser emery had practically disappeared; at the same time the form of the thread had been well maintained, and the gauging was uniform and good. It was therefore decided to proceed with the next finer grade of abrasive, viz., .0005 inch alundum and carborundum in equal parts; the grinding operations and other procedure being exactly similar to those of the preceding grade. It was noticed, almost at once, that this somewhat finer abrasive had a different grinding sound, and somewhat smoother action, appreciable to the touch when the nut levers were held by hand for a short time. A longer time was given to grinding with this particular grade, the work extending over the greater part of a month. The improvement effected could then be easily appreciated in the smoother movement of the nut, apart from that seen under the microscope, which was satisfactory throughout the full length of the screw. It was therefore decided to use one of the finest grades of emery and carry on the grinding with this to a finish. This work occupied another week or more, and proceeded satisfactorily, although the effect upon the screw was less pronounced than might have been expected.

As it now appeared that little further improvement could be effected by grinding, both nut and screw were carefully cleaned, and the latter slightly polished with the harder residueo of washed rouge, that is the purplish portion, which imparted a slight gloss only to the finished work.

The screw having been freed from all traces of polishing material, the nut was traversed to and fro upon it, with a trace of oil only, and pressure just sufficient to ensure the closest approximation to contact with the screw which could be obtained without risk. As this procedure gave no indication of inequalities of pitch or diameter, and direct microscopical examination and comparison by the methods described was equally satisfactory, it was decided to mount the screw in its permanent position upon the bed of the machine, and submit it to the test of an acutal ruling or series of rulings, in order to determine under working conditions its accuracy and other behaviour. Preparatory to this step, it was necessary to cut away a portion of the threads from each end of the screw, to provide space for bearings and the ratchet head. To effect this, the original centres of the screw bar were availed of for the preliminary turning down to obtain a first approximation to the limits of accuracy required. As the original axis of the bar and that of the ground thread were probably no longer coincident or parallel, and as it was of the first importance that the thread axis and bearings should be strictly in alignment to ensure this condition, the grinding nut was first mounted upon the lathe carriage, so as to travel approximately parallel with the ways of the bed: the screw was then threaded through the closely fitting nut. The bearing portion of each end of the screw was next slowly revolved and advanced past a small fine carborundum grinding wheel, running on the dead centres of the lathe, at about 5000 revs. per minute. This plan of "truing" the bearings ensured a very close agreement between the thread and bearing axes.[1] The two bearings thus ground were then available for correcting the centre holes on which the threads were first cut, so that eventually, centres, bearings and threads were found to be in such close agreement that the usual mechanical tests applied to them indicated no appreciable error.

As we are not here concerned with the work intermediate between what has just been described, and certain further corrections made at a later period, and which resulted in the practical elimination of all measurable irregularities between screw, nut and bearings, we may at once proceed to describe how this further improvement was accomplished.

III.—*Final method of adjusting and testing the screw and its bearings.*

It has already been stated that the ruling machine was completed up to a certain stage, and a number of trial ruling made under unavoidably adverse conditions. As was anticipated, the results from these early trials were imperfect but valuable in that they served to bring under notice defects of various kinds. Among these one was such as could have been caused either by a bent screw or by a screw whose axis was eccentric with its bearings by amounts too small for the rough methcd already described to detect.

After some experiments had been made, the following device for the detection of small errors in the screw or its bearings was designed and constructed, and proved both convenient and effective. An inspection of Fig. 2, Plate XIV., which is a plan of the apparatus, will aid the verbal description here given.

As a sufficiently sensitive test could not be directly applied to the screw when in position upon the ruling machine, both screw and nut were detached and placed in polished steel V-shaped bearings, secured to the carefully worked surface of a heavy slab or surface plate of glass about $1\frac{1}{2}$ inches thick. The strict alignment of the V bearings with respect to each other was obtained by first placing upon them a straight round bar of steel accurtely ground to the same diameter as the bearing surface upon the screw. The use of this bar ensured the parallelism of the V block surfaces.

1 This method of correcting the bearings assumes the straightness of the screw; an assumption which afterwards was found to be incorrect.

The glass slab carried, in addition to the screw and its bearings, a long rectangular bar—also of glass—lying parallel to the screw, and serving as a guide and support for the extension lever bar of the nut, in a position identical with that occupied by the same parts upon the ruling machine when in action. Hence the nut could be traversed from end to end of the screw, without the slightest movement in rotation. A second long rectangular bar—In this case of machined iron lying parallel to the screw, but about 6 inches from it, was also secured to the base plate. This iron bar served mainly as a guide for a smaller bar or block of iron supporting a small travelling microscope which could be moved in a direct line from end to end of the screw. The microscope was fitted with an objective and eye-piece, affording a combined magnification of about 25 diameters; the eye-piece being fitted with a micrometer scale having 100 scale divisions within the field of view. The V bearings supporting the screw were both exactly of the same dimensions and height, and one of them was provided with a thrust plate enabling the screw to be rotated without end play. For convenience in rotation, and recording of positions, the other end of the screw was fitted with a simple graduated disc and short lever handle.

The swivelling steel ring surrounding the nut carried a carefully made parallel plate of quartz about $1\frac{1}{2}$ in. long by $\frac{5}{8}$ in. in width, and thick enough to prevent flexure. One face of this plate was cemented to the steel ring in a horizontal position, while its outer face, which was optically true and polished, could be brought to a position strictly in alignment with the travel of the nut, and therefore of the screw axis, an essential condition for this method of testing.

This agreement was arrived at by trial and error, the quartz plate being adjusted so that a longitudinal movement without rotation of the screw in the V bearings caused no change in the position of the indicator (described below) as seen in the microscope.

To complete the testing equipment, a delicately sensitive lever indicator was constructed. This was provided with adjustable bearings and a needle index bar with a magnification ratio of about 1 to 20, with respect to its length and fulcrum adjustment; or with the microscope a combined magnification of 500 diameters. The index point of the needle moved in a vertical plane across the scale of the miscroscope eye-piece, and was adjusted, when in use, to indicate a movement of rather less than one micron per division of the micrometer scale and values of less than half that amount, or 1/50000 inch were both appreciable and reliable. In operation the lower bearing point of the indicator—a polished steel sphere—was brought into contact with the face of the polished quartz plate just mentioned, the indicator needles being inclined at about 45°; an angle both correct and convenient for the position of the microscope reading scale, and other predetermined constants of the apparatus. These various adjustments called for the expenditure of some little time and care at the outset, but any difficulties were soon mastered and the instrument proved reliable and effective throughout its subsequent use.

As soon as the foregoing method afforded the necessary assurance of reliability, a series of tests were made and the readings carefully tabulated, the results being recorded in graphic form. One of the graphs, the earliest obtained, has been reproduced as Fig. 1, Plate XIII., and will serve to illustrate the actual condition of the screw at this time, before any attempt had been made to correct the errors revealed by this method of testing. Seeing some explanation is necessary to make clear the interpretation of the results obtained from the measurements and graphically recorded as Figs. 1, 2, Plates XIII., and Fig. 1, Plates XIV., we may first indicate the procedure followed in obtaining the data for constructing the graphs here presented.

The curve in the upper part of the figure was based upon a record of some 16 readings (see below) taken at half-inch or 10-thread intervals over the full length of the screw in the following manner. The three-inch nut was first carefully fitted to the screw and run into position, back towards the thrust end of the screw up to the limit of the threads available, all the threads of the nut being engaged. With the spherical end of the indicator in contact with the quartz plate, the screw was slowly revolved through a complete turn, the observer meanwhile noting any change of index point, in relation to the scale in the field of the microscope. It is here worth drawing attention to the fact that the maximum and minimum readings always corresponded with the same points on the divided circle used for locating these positions, indicating that the bend upon the screw was of the nature of a *plane* curve.

A record of the mean deviation of the index per revolution for three revolutions, was usually made for each position. This was done for every half-inch interval over the range of threads available for measurement. The set of readings here given was obtained before any further work was done on the screw by way of correction.

Distance from zero position.		Microscope deflection.	Distance from zero position.		Microscope deflection.
0″	-	30.5	4.0″	-	44.5
0.5	-	32.5	4.5	-	44.5
1.0	-	33.5	5.0	-	43.0
1.5	-	35.5	5.5	-	43.0
2.0	-	40.0	6.0	-	41.5
2.5	-	40.5	6.5	-	39.5
3.0	-	43.0	7.0	-	37.5
3.5	-	43.0	7.5	-	37.0

The method employed in plotting these observations was as follows :—

In the figure (1, Pl. XIII.), the abscissae along the line O X represents the distance of the centre of the nut from its position at the first observation where the abscissa $=0$; measuring the first reading or its reduced value from O and the last reading (that at $7\frac{1}{2}$ in.) from X both downwards we obtain the points A and B respectively. Then using the straight line A B as base line, all the intermediate readings were plotted by measuring them upwards from A B. Thus we obtain the curve O M X which represents graphically the shape of the screw between the points where the nut was situated at the first and last readings. Thus at the point on the screw represented by M, the interval N M represents the sum of the errors of bend and eccentricity, M P representing the ordinate at M of the curve formed by the screw, and P N the amount by which the screw is "drunk" at M due to bearing eccentricity; the actual amount of error in each case being given by the scale on the diagram.

With respect to the value of the microscope readings mentioned above. One division of the microscope scale was actually .00009 cm. but for convenience the observed readings, which obviously were twice the actual error, were plotted in each case. The inch values given as a scale to the diagrams are approximate only and represent the errors, not twice the errors.

Regrinding the Screw.

Progress and results at intervals of from 3 to 5 hours.—The series of curves shown in Fig. 2. Pl. XIII., have been prepared in order to illustrate the improving shapes of the screw as re-grinding proceeded. The base or reference line A B of Fig. 1 has, however, been omitted in Fig. 2 for convenience. In all the tests the values of the negative ordinates O A and X B remained the same, within the limits of experimental error, as in the case of the first test (Fig. 1).

With respect to Fig. 2, the first of the four curves is that already described Fig. 1, included for direct comparison. The second curve shows the result of 15 hours' work, and is the fourth recorded during this period. It clearly shows the reduction of the original error to about one-half. The third curve was drawn after a further period of grinding, with the same abrasive and for about the same time as before, and with the same proportion of improvement. Afterwards the grade of[1] abrasive was reduced to .0003 in.—emery in this case—and the grinding continued at a slow rate for some hours longer. Finally, the result shown in curve 4 was obtained and was deemed satisfactory.

It now remained to correct the eccentricity of the bearings. To effect this no better plan than the one previously tried could be devised; it was therefore followed, and as the screw was now straight, with entirely satisfactory results, as may be seen in Fig. 1, Pl. XIV. Here the curve O X and base line A B were plotted exactly as in Fig. 1, Pl. XIII., and it will be seen that the negative ordinates O A and X B which represent eccentricity, have been reduced to about .00002 in. and .00003 in. respectively, a condition which it would be difficult to improve with any certainty of success. The results from these two improvements, combined with minor adjustments, have been evident throughout all subsequent ruling.

2.—The Ratchet Head.

The construction of the Ratchet head or wheel differed in some respects from similar parts of other ruling engines. These parts, so far as they have been described, have usually been made of brass or gun metal throughout; probably for ease and convenience in cutting the teeth.

It was decided in this case not to follow the usual practice, but to construct a composite head of gun metal and steel; the hub, with a flange for supporting the steel rim, alone being gun metal. As the general design and construction of the head are well shown from various view points throughout the series of plates illustrating the

1 Alundum, grade ·0005″ had been used up to this stage.

machine, it is not proposed to enter upon a detailed description, but merely to specify the principal dimensions and essential features. The central hub and the flange for supporting the steel rim were turned from a single casting of hard gun metal; the hub being about $1\frac{1}{2}$ in. through and made to fit the corresponding tapered bearing upon the screw. The flange of the hub was about 8 inches in diameter and formed the bed and support of the circular steel rim. The over-all diameter of the rim was 10 inches and its finished thickness just under $\frac{1}{4}$ inch. This steel rim, which was turned, annealed and afterwards ground and lapped with great care, was accurately fitted and bolted to its gun metal support without avoidable stress of any sort, and with only just sufficient freedom to accommodate for any differenec in expansion.

Two similar heads were thus constructed; in one 360 and in the other 540 teeth, were eventually cut. The cutting of these teeth with the necessary accuracy was a formidable undertaking, and occupied a long time. As no milling machine possessing even approximately the accuracy required for cutting the teeth was available. it was decided to grind them out, a method which, although slow and laborious, promised to afford accuracy of a fairly high order. The first requisite for the method proposed to be followed was a well divided circle. Therefore, with a view to securing one sufficiently correct, a number of theodolite and other circles were examined and tested as to their correctnes; but all failed in this respect. Hence it was decided to have a circle constructed and specially graduated. Messrs. Watts and Son, of London, who had recently built a very accurate circular dividing engine, were communicated with, and they undertook the work of making and graduating a suitable disc of silver. On this circle each of the 360° was divided into 10 minute intervals with graduation lines sufficiently fine to bear a magnification of 100 diameters. The completed circle fully met expectations, its accuracy being well within the limits stipulated for, viz., $\pm$ 2.5 seconds. Indeed, after a series of tests we found its accuracy comparable with that of a circle ruled by the same engine under approximately the same conditions and tested by the Imperial Institute, Charlottenberg. The maximum error of any sort found in the latter were $+1.4$ seconds and -1.7 seconds.

The provision to be made for the actual operation of grinding the teeth was next considered and was mainly worked out as follows:—A number of specially thin dental wheels, 3 inches in diameter and made of the very hard greenish variety of carborundum, were obtained. Each wheel was mounted upon its own steel spindle, from which it was not again removed, and with the aid of suitable diamond tools its periphery was trued and cut to the shape necessary to reproduce by grinding the form of teeth required. The wheel spindles were adapted to run in a lathe cutter frame with hardened centres, with overhead drive and provision for speeds up to 6,000 revs. per minute as free as possible from vibration. A series of wheels were thus fitted varying in grade of grain, but all relatively fine and made up with a vitreous bond. The coarsest of these wheels were used as originally made for the first roughing cuts in which extreme accuracy was not called for. But the carefully formed edges of the finer grade wheels, used for finishing the teeth, in which process both great accuracy and high finish were required, were charged with diamond powder obtained by crushing and grading after the method described for preparing other fine abrasives. This grading was of course done on a proportionately small scale and with the aid of petrol in place of water. Several grinding discs were so charged, each with its own grade of diamond in the following way:—

The spindles, carrying each its own wheel finally trued and turned to the correct shape, were supported on centres in a small frame convenient to a tiny blow-pipe flame arranged to impinge upon the edge of the disc and parallel with its face. The disc or wheel, carefully freed from grease or dirt of any sort, is then slowly revolved and its edge moistened with a strong solution of soda carbonate, using a fine camel-hair brush and working with the aid of a magnifier, which is necessary as the dimensions of the trued edge of the disc are very small. The application of the alkaline solution ensures the even distribution and adhesion of a film or layer of a thin cream (made up with water) of glass enamel composed of extremely fine ground moderately hard glass, containing about one part in three of diamond powder of the particular grade suited to the work to be done. The liquid enamel thus prepared, fills up the pits and crannies in the edge of the disc, which are of course very small in the case of a fine grade wheel. As soon as the layer of enamel is dry, that is in a few minutes, it is ready for firing. To effect this the wheel and spindle are first slowly and uniformly heated with a bunsen flame, after which the blow-pipe jet is brought into position to play quietly upon the extreme edge of the disc, which is quickly brought to a white heat, fusing the painted on enamel (which binds the diamond dust) to a thin vitreous coating on the edge of the wheel. The fusing process requires care, skill and judgment. The wheel during the process is slowly revolved and kept under observation with a magnifier. More than one coating of enamel will usually be required to ensure an enduring result. It will be understood that this treatment does not injure or fuse the diamond fragments, which, if small and uniformly graded, remain securely embedded in the enamel, filling the minute cavities of the wheel edge. As the thin outer skin of the enamel wears away when the wheel is in operation the diamond particles are exposed; hence after a little preliminary use, the wheel edge when used for cutting or grinding purposes which require prolonged endurance and permanence of shape, becomes the equivalent of. a diamond wheel. It is, however, important that during is use, either upon hard steel, glass, or any similar substance, the precaution not to overfeed or force the rate of cutting be strictly observed. With due attention to these precautions the "life" of the cutting edge of the wheel may be greatly prolonged. The art of using such a wheel correctly and effectively can only be gained by experience.

The method of mounting and moving the ratchet head had next to be provided for. The arrangements made for this purpose, also for supporting and revolving the graduated circle and for maintaining in a rigid position the two reading microscopes used upon the circle, are sufficiently illustrated in the photograph, Pl. XV. This photograph, if carefully examined, is self explanatory in respect to almost every detail. Some of the principal features shown therein, apart from the lathe and its fittings, are, first, the steel rod forming the spindle on which are mounted from left to right in order—the ratchet wheel, next to this the tangent-wheel and its fittings for moving and clamping the whole system during work upon the ratchet. Finally the Watts divided circle for spacing and controlling all angular movements upon the ratchet. The ratchet wheel and divided circle were most carefully centred and correctly related to each other by grinding the spindle on "dead" centres and making full use of the two microscopes in the adjustment of the reading circles. Once these adjustments were effected the ratchet and divided circle were never displaced relatively to each other during subsequent grinding operations upon the teeth. The microscopes were securely mounted upon the thrust bar or socket of the back centre which also provided for rotary swing and rough focussing adjustment. Fine adjustments of the microscopes were effected by means of the sleeves carrying the tubes; provision was also made for a certain amount of lateral displacement. The optical equipment of the microscopes afforded a magnification range of from 50 to 100 diameters which was found to be ample for all purposes. The steel spindle, carrying the whole system, was supported on the two " dead " centres of the lathe, which were secured in a "locked " position. The cutter frame, supporting the grinding disc and guide pulleys, is seen in a working position immediately in front of the ratchet wheel. During the operation of cutting the teeth the main carriage or saddle of the lathe bed, in the tool holder of which the cutter frame was clamped, was traversed along the ways of the lathe for the short distance, usually less than an inch, required to complete the cut and clear the ratchet. To effect and control this movement, the apron mechanism of the lathe carriage was made use of and proved to be both steady and reliable.

During work upon the ratchet, and particularly near its final stage, provision was made for protecting the more sensitive and exposed parts of all mechanism likely to be affected by heat from the operator's body or other source liable to lead to expansion or contraction owing to temperature changes. The cutting wheel, which was absorbent, was maintained in a moist condition with kerosene, derived from a sponge pad in contact with its edge. Hence the heat produced by the operation of grinding was reduced to a minimum.

In the course of the final finishing work upon the ratchet wheel, the whole of which was effected with the diamond charged discs already described operating with cuts of .0001 in. or less, a greatly improved grinding frame (not shown in the photograph) for holding the grinding cutters was used. Hence the combined outfit worked with such precision that it was possible to grind completely round a circle of 540 teeth and find hardly any appreciable loss upon the wheel cutting edge due to wear, although the operation involved over 2,000,000 revolutions of the grinding disc. A result of such a nature would have been quite impossible without the aid of the special appliances with which it was effected.

Reference to one or two other details affecting grinding operations may here be made. In order to save time, the angular feed of the ratchet through a tooth space was effected by means of the tangent wheel during four-fifths of the time occupied in the process of grinding out the teeth. During the finishing process, however, in order to eliminate all stresses, the tangent wheel was thrown out of action and direct adjustment upon the divided circle with the aid of the microscopes was made by hand. Once this adjustment had been made for each tooth, the whole system was clamped and remained rigid during the passage of the grinding disc across the tooth face. The precaution to complete each circuit of the wheel at one operation without a break was always observed. Furthermore, every fresh traverse was commenced a quadrant to the rear of the one preceding it. Adequate provision was also made to eliminate so far as was possible the chances of error due to fatigue or interruption; the latter being by far the most difficult to provide against.

It now remains to indicate in general terms the probable degree of accuracy which was attained by the foregoing method of cutting a ratchet wheel. Prolonged tests with a view to determine the nature and extent of the inaccuracies upon the circuit of the ratchet were made. Necessarily errors are present even in the most carefully executed work of the character just described. It was hoped that, assuming necessary precautions had been taken throughout, the degree of accuracy present in the divided circle which was copied could at last be closely approximated, especially as the original errors of this circle, which had already been proved to be small, were bisected by the use of two microscopes in the adjustment made for every tooth cut.

Among the various tests made to determine the extent of remaining inaccuracies, was one which involved the use of a test indicator, not unlike the one already described and used for testing the screw. In this case, however, it was made and fixed so that it engaged the working face of a tooth similarly to the way in which the pawl engaged it. It was so fixed that, as the ratchet wheel was moved on the ruling engine by the pawl, it engaged first the teeth distant 180° from the pawl, and readings were taken. Then it was placed at other distances as required in the usual methods of calibrating divided circles. This test was carried out upon the ruling machine under conditions, so far as individual teeth were concerned, analogous to those in operation when ruling. The magnification used to detect movement of the index in the field of the microscope was such that a movement indicating an error of one-thousandth part of a tooth interval could be read with ease. The result deduced from a series of tests by the above method indicated that the maximum error of any single tooth throughout the circumference of the ratchet was less than one-600th part of a tooth space and no periodic error was perceptible. Unfortunately the limits of this paper preclude any detailed statement concerning the manner in which these investigations were carried out.

3.—The Thrust Plate.

The thrust plate or bearing surface against which the screw rotates is of great importance, in that any imperfection or weakness of its surface or any diversion from a strictly normal position, of even a small area of its surface, may result in some error or slight disturbance of the screw which is almost inevitably communicated directly to the ruling. Hence a thrust plate must be made of material combining the properties of compactness, hardness, toughness and durability in a high degree. This material, whether natural or artificial, must also be such as is capable of receiving the highest possible optical finish, that is, with respect to the perfection of its working or bearing surface. The importance of these requirements will be appreciated when it is borne in mind that errors resulting from imperfection of a thrust bearing will be periodic and if so an error of amplitude less than .0000005 in. would be quite appreciable by its effect on the finished grating. Thus in the selection of a substance suitable for a thrust surface we are restricted to an extremely limited choice of material. Naturally, to those familiar with the limitations and requirements involved, the diamond is at once suggested as the most likely substance to adequately fulfil all the demands made upon it. Unfortunately a diamond of a suitable size and shape for the screw thrust of a ruling engine would be difficult to procure, extremely costly and almost impossible to work, without professional aid, to the requisite perfection of surface demanded. Of other substances we only propose to mention those of which we have had actual experience, and know wherein they failed to meet requirements. Naturally, of the substances experimented with, only the most perfect examples obtainable were used. These included the hardest steel, crystalline quartz, agate, topaz and sapphire.

The steel thrust plate was promptly discarded; though hard and tough and worked to a highly finished surface, it required lubrication to prevent seizure and this at once introduced instability, owing probably to the varying thickness of the oil film. Moreover, with steel against steel (the screw terminal face also being steel) signs of wear were soon apparent. The two examples of quartz which were tried, afforded, for a time, some promise of success and permanence; eventually, however, minute circular scratches or grooves appeared on the area of contact with the screw facet, which led to their rejection. Topaz, which is only a trifle harder than quartz, and not so tough as the variety of quartz known as agate, likewise failed, and probably from the same cause as the latter.

With respect to sapphire, this was actually one of the first substances made use of, and was only temporarily discarded because of the difficulty of working up a bearing face to the requisite perfection. A second attempt to prepare a fine crystal slab of this gem, after the rejection of steel, agate and topaz, was rewarded with a greater measure of success; the result from the second attempt being a finely polished optically true surface, over a central circular area of the crystal $\frac{3}{8}$ in. in diameter. This face, which was free from defects, either of its crystalline structure or those arising from the process of working it, was formed on the face of a square slab of sapphire $\frac{3}{4}$ in. in diameter and under 3-16 in. thick. Two sapphire thrust plates have been successfully prepared. One of them, which is circular in shape, has been cut from a synthetically formed crystal of sapphire. The latter is somewhat easier to work than the natural gem, probably because the crystalline cleavages are less developed. The artificial gem, however, has the disadvantage of being less perfectly annealed, and, in consequence, requires greater care in working to avoid fracture. The following outline of the process of working a true sapphire thrust face may be worth recording, as it differs from the lapidary's method of working such gem faces.

It is necessary in the first place to secure a good sapphire gem stone, its colour is immaterial; it should, however, be fairly large and quite free from cleavage fractures and other similar defects. The work of slicing and roughly cutting to shape is done after the method followed by the lapidary; the grinding and polishing of its faces requires more exact treatment than he usually gives to these operations. In order to obtain good surfaces, truly worked and free from scratches or other defects, three small laps were first prepared and ground true on one face. One of these laps, made of gun metal, was used, with finely crushed and separated diamond powder, to grind up the faces and edges of the sapphire plates until they were fairly smooth and parallel. A second lap, of steel in this case, with still finer diamond powder, sufficed to finish off one ground face until it was free from the scratches and pitting remaining from the preceding grinding. A third lap of pure tin, with a carefully prepared face, was now used for polishing the already optically true face of the crystal; the polishing material being extremely fine diamond separated in oil. If the polishing operation is properly carried out it leaves the surface of the crystal optically true, scratchless and with a brilliant polish. The outer zone of the rectangular face of the crystal was next turned off in the lathe, with the aid of a diamond tool, leaving the central area circular in outline and slightly above the surrounding face (see Fig. 1, Plate XVI.). The task of grinding and polishing the plate was throughout controlled and corrected from time to time, as required, with the aid of a small test plane, in order to ensure the best possible result. Any trace of error, when tested in this way, should nowhere exceed some small fraction of a wave length. This condition is attainable with time, patience and a moderate amount of manipulative skill.

It remained now to provide for the *Mounting* and *Adjustment* of the thrust plate prepared as described.

With respect to the former, viz., *Mounting.* The plan adopted for mounting the prepared thrust plate was as follows:—A block of machined cast iron was first prepared. This in elevation was triangular in outline with rectangular base and perpendicular face. The base was 1½ in. square, the perpendicular face 2 in. high. Plate VI. shows the position of the thrust in relation to surrounding parts of the machine; also the method of its attachment to the bed. Fig. 1, Plate XVI., is a photograph, slightly enlarged portion of the perpendicular face of the block, the upper part of which shows the method of attaching the crystal plate to its bed. This attachment was effected with the aid of a small rectangular frame the inner edges of which were undercut to fit the bevel upon the edges of the crystal plate. The latter was then inserted into the frame in which it was embedded with a suitable cement composed mainly of shellac. By this means the thrust plate is made both secure and rigid within its frame without undue strain, while at the same time its face is adjusted approximately perpendicular to the base of its support.

Final adjustment of the thrust plate and screw thrust.—As there is a mutual relationship between the sapphire thrust plate and the screw thrust, their respective adjustments may be treated concurrently.

The shape of the screw thrust finally adopted was that of a blunt cone of hard steel with a small flat termination, the diameter of the latter being about .1 in. This form of thrust, up to the present, has behaved satisfactorily and promises to prove permanent, as it has now been in use for a considerable time.

Although it may not be absolutely essential that *both* thrust faces should be strictly parallel and perpendicular to the screw axis, one of them must be exactly so placed and the other as nearly so as possible; hence the adjustment of both was effected as part of the same operation.

In the first place, the cone and flat of the inserted screw thrust was ground with all due precaution in the lathe and a surface approximately perpendicular to the axis of the screw was obtained. This, however, was not accurate enough for the purpose required and, as the further adjustment of the end of the screw was related to that of the sapphire face, the method adopted for their mutual correction will be explained with the setting up of the thrust block. In order to obtain a close approximation to its true position the sapphire thrust block was first set up with the aid of the usual mechanical appliances. More exact adjustment was obtained by the use of a well-known optical method of setting up a mirror normal to a rotating axis. A round bar of steel, rather longer than the screw, was accurately ground at each end to the same diameter as the screw bearings. This bar formed the counterpart of the screw without its threads, and hence could be used with greater freedom and without risk. To one end of the bar, representing the thrust end of the screw, a truly plane quartz mirror was attached by means of a slightly plastic cement. This rod was placed in the bearings of the ruling machine, and the mirror firmly pressed without rotation against the sapphire thrust face. The rod was then transferred to V bearings so placed that by means of a reading telescope of fairly high power a distant illuminated disc with cross wires and perpendicular scales could be viewed by means of the quartz mirror. Rotating the rod caused the image of the cross wires to move in the field of view unless the surface of the mirror was normal to the axis of the rod. Definite movements corresponded, as was soon found, to definite errors in the thrust and so by means of trial and error the thrust was, after considerable work, adjusted until the image of the cross wires remained fixed during a rotation. As the sapphire thrust had already been adjusted to a nearly correct position, these later adjustments were only of microscopic dimensions. For adjustment in a horizontal plane, the small movements required were effected with the aid of two micrometer screws placed one on the right and the other on the left of the thrust block to which they could be made to impart a minute rotary movement. Adjustment of the block in a vertical direction was obtained by slightly grinding either the front or back surface of the block base as required. The effect of every adjustment was determined with the telescope and was followed by such further alterations as was indicated by the motion of the image of the cross wires. The process of correction was continued in this way until the telescopic image remained steady within the limits of experimental error. Finally the mirror was removed from the rod representing the screw and was placed upon the actual screw of the machine and a slight further adjustment of the thrust plate made by the same method.

As the thrust block could now be removed and restored to its position between the micrometer screws with certainty, it was taken out and the surface of the sapphire coated with a very thin film of a solution of eosin in alcohol and water, applied with the aid of a fine smooth needle. In this way an immeasurably thin film of stain or colour was left upon the polished sapphire face. On replacing the block in its former position the thrust facet of the screw was gently pressed into contact with the sapphire and rotated through a very small angle. The effect produced was carefully examined with a powerful magnifier and the exact position and area of contact determined; this showed that the surface of contact was not central but was limited to one part of the thrust near its edge. Another test with the screw 180° from its former position definitely indicated that the screw facet was principally at fault. Correction of this defect was obtained by inserting a thin parallel plate of quartz between the thrust plate and screw bearing; one face of the quartz was polished the other smoothly ground, the latter being in contact with the steel thrust. The screw was then slowly rotated in contact with the plate which was constantly moved, revolved and reversed between the thrusts. The result of these combined movements was a delicate abrasive action upon the screw facet without any corresponding effect upon the sapphire thrust face. In this way, with care and judgment, fairly uniform central contact of the screw thrust face with that of the sapphire was obtained. It should be understood that the amount of material removed from the bearing surface of the thrust by this process was probably not more than one or two wave lengths in thickness. These correctional operations, which extended over a considerable period, with intervening trial rulings, resulted eventually in the almost complete elimination of any remaining periodicity.

4.—The Diamond.

Under this heading it is proposed to allude briefly to the minor but yet essential mechanical appliances for adjusting and controlling the movements of the diamond during the act of ruling. The principal features of the mechanism of the ruling carriage have already been described and a short account given of the sequence in which certain movements took place during the process of ruling. (See page 49.) The following remarks so far as they relate to the mechanism controlling the diamond, are supplementary to the previous description.

Figs. 2 and 3, Plate XVI., are photographic views, back and front respectively, of the ruling mechanism. Fig. 3 shows in some detail the following parts:—(1) The bar of hard steel of square section supported in a steel frame with the aid of two hardened conical screw pivots which permit of movement in arc of a few degrees. Secured to this bar on its lower face there is a plate of hard steel (37),[1] triangular in shape, in the centre of which the principal dash well (42) is placed, the diamond holder being secured to its apex. This holder is a small hollow cylinder (38) of aluminium with solid end whose walls are partly slotted through to hold the diamond clamp (39). The attachment of the solid end of the cylinder to the triangular steel plate provides for rotational adjustment. Three important movements of the diamond are provided for in this form of holder, viz.: (1) axial rotation of the rod or pin on which the diamond is mounted; (2) movement of the clamp block 39 in a vertical plane parallel with the direction of the lines ruled; (3) movement in a direction or plane at a right angle to the direction of the lines ruled. All these movements are important in the preliminary setting up of a diamond. Two steel rods complete the control outfit of the diamond; one of these (4) is made to lift the diamond from the plate after each line has been ruled, the other supports the plunger of the dash well and is not shown by the photograph.

In Fig. 2, Plate XVI., we have a back view of the diamond carriage and its fittings. Here may be seen an oblong block of metal secured to the suspension bar and serving as a counterpoise to the triangular frame and fittings of the diamond holder. This block in addition to acting as a counterpoise is fitted with two additional oil wells and dashers and also carries a projecting

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1 The numbers refer to positions and parts indicated by corresponding numbers on the plan of the machine, Plate VI.

threaded bar on which additional weights are screwed for regulating to a nicety the pressure upon the diamond ruling point. The ruling system is thus completely controlled and balanced upon the two hardened centres of the suspension frame.

Considering the long period during which interest has been more or less centred upon fine ruling and the means for accomplishing it, either for use as spectroscopic gratings, test rulings or micrometers—all of which require very fine accurately spaced lines—but little has been written concerning the diamond with which such ruling is effected. As already mentioned, Nobert guarded with jealous care his knowledge of the subject, the result of years of patient work, and which he regarded as an important secret known only to himself. Upon Nobert's death his ruling machine passed eventually into the possession of the late Dr. von Heurick, of Antwerp, who was interested in ruling in its relation to the microscope. Some years ago the writer had correspondence with Dr. van Heurick, who stated that he had spent some time in trying to rule test plates similar to those prepared by Nobert, but without success. In the course of his experiments he had had prepared by one of the most skilled diamond workers in Antwerp a set of diamonds exactly similar to those found with the Nobert machine and with which Nobert presumably ruled his plates. Dr. van Heurick generously presented to the writer three of the prepared stones. Whilst it was a matter of great interest and pleasure to obtain these diamonds, the knife edges of which appeared to have been exquisitely worked, the results obtained by their use were most disappointing. Indeed the lines obtained with these carefully prepared knife-edged gems were quite unsuited for any but the coarsest ruling. Prior to this experience with the diamonds from Dr. van Heurick, an interesting paper by Profesor Rogers, of Baltimore, U.S.A., had appeared. This paper contained much information concerning the operation of a ruling diamond with prepared knife edges and with edges resulting from fracture; the latter were stated to be more or less unsatisfactory. His method of using either knife edges or fractured splinters appears to have been diametrically opposed to that of other workers; certainly to that of the writer.

Professor Rogers, for example, emphasises the statement that a ruling diamond should produce, or did in his experience produce, a distinct and characteristic sound during the act of ruling. So familiar had this note become to his sense of hearing that he was accustomed to judge of the behaviour of a particular diamond by this characteristic note. The writer's experience, extending over some 20 years, of the behaviour of a diamond during the act of ruling is that its action should be practically free from any appreciable sound or note of any sort. Anything approaching a distinct hissing or singing note has invariably been regarded as evidence that the lines thus being ruled would show, when examined miscroscopically, some indication of a vibratory or chattering effect upon the surface ruled, and that the "life" of a diamond operated under these conditions would be comparatively short. Apart from this somewhat contradictory position with respect to the experience of others whose work has extended over a considerable period, the article referred to contains much interesting information.

One other reference to the action of a diamond when ruling appears in the collected Researches of the National Physical Laboratory, Vol. VIII., 1912. The results therein embodied have presumably been derived from experience in ruling with the Blytheswood Engine. So far as the *method* of using a diamond is there explained, the writer is in full agreement; with certain other statements and procedure there recorded his experience is at variance.

With respect to the choice and selection of diamonds suitable for ruling. After an experience extending over 20 years the writer prefers diamonds found in the diamondiferous drifts of New South Wales. These stones are both harder and tougher than any other he has hitherto obtained. Both Cape and Brazilian stones have been tried; also the so-called black diamond, carbonado and "bort," nearly all the varieties of which are more or less crypto-crystalline and unsuited for ruling except for the coarsest lines. The best Australian stones for ruling work are those showing smooth, bright crystalline faces, the simpler octahedral forms affording the best results. The more complicated the crystalline structure, the fewer the splinters adapted for ruling obtainable from a given gem. Cleavage fragments intersecting the smooth outer surface of a stone frequently give excellent results and are very durable.

For breaking the stones, a small mineralogical hammer and hard steel anvil are required, with provision to prevent loss of flying fragments. Straight smashing blows must be avoided or the stone will be reduced to dust. A dragging blow ranging from a sharp tap to one of considerable force may be used; changing the position of the stone until success is attained. 20/- worth of selected stones will serve for a lifetime if properly used. Once a stone has been broken into several pieces a gentle blow will serve to reduce the larger fragments to a suitable size for ruling purposes. The broken splinters are placed in a watch glass and roughly sorted from the small debris. The selected pieces are then carefully examined under a higher magnification and those showing good knife edges and cleavage faces intersecting a smooth outer crystalline face, may be selected for trial. After a sufficient number have been thus obtained they are mounted in cup-shaped depressions drilled on the ends of short pieces of straight hard brass of the correct gauge to fit the holder of the machine. The depressions in the rods are partly filled with a hard tough cement rendered plastic by heating. The diamonds are placed in position upon the cement which is gently heated and moulded around the diamond fragment until the latter is deemed to be secure. The whole of this work is done with the aid of a microscope and requires both care and experience. A popular notion concerning diamonds is that they are so excessively hard that they may be handled with impunity. This notion is speedily falsified upon a very short experience of the fragile edge of a diamond suited for ruling lines at the rate of 20,000 to the inch.

When a few promising fragments have been cemented in their holders they are placed in a small ruling machine, and tested with respect to correct centring and inclination or angle of the knife's edge to the surface being ruled. The setting of a diamond for ruling is almost the reverse of that required when it is used as a turning or cutting tool upon a lathe. When used for the latter purpose, it is required of a diamond to definitely remove materials from a given surface. As a ruling instrument the diamond usually only slightly displaces or compresses material according to the nature of the material. The lines, for example, represented in the photographs, Plate XVII., are nearly all examples of slight displacement or compression. Moreover the diamond is not rigidly held during the act of ruling but is trailed along the surface operated on.

The pressure exerted upon the cutting edge of a diamond must be carefully proportioned to the length of its contact with the surface ruled, and this does not usually in the case of fine lines exceed .002 in. The angle the cutting edge makes with the surface ruled upon must at the same time be taken into account, as this angle has an intimate relation with the length of contact on the ruled surface and hence with the pressure required for a satisfactory line.

With respect to lines suited for diffraction gratings they must be clean and sharply defined and for normal light distribution in the different spectra the groove should be symmetrical or isosceles with respect to the ruled surface. The length of service of which a diamond is capable depends very greatly upon the treatment to which it is subjected. The shock which a diamond gets due to its fall at the commencement of each fresh line has a more detrimental effect upon its cutting edge than the wear due to the act of cutting. A ruling diamond in the case of grating ruling should have its fall restricted to less than .02 in., and the blow from even that height must be carefully moderated with damping devices or the character of the line will change as the ruling progresses and the resulting grating rendered valueless.

In order to illustrate several of the most common defects resulting from the improper adjustment of a ruling diamond, a few photographs of rulings have been prepared and are shown in Plate XVII. Two of these photographs (Figs. 1 and 2) were taken to show the character of lines resulting from a correct adjustment of the ruling diamond. Only the starting and terminal ends of the lines were photographed as these show most clearly that the diamond has been correctly adjusted. These lines were ruled at the rate of 1000 to the inch by hand which accounts for any slight irregularity. The diamond with which these lines were ruled had been in use for some weeks and had ruled several hundred thousand lines with apparently no change in its condition. Fig. 3, Pl. XVI., shows a group of lines ruled upon speculum metal with a slight displacement of the diamond edge from a position parallel with the line ruled and also slightly tilted from the perpendicular. The effect produced is sufficiently striking. The diamond, in cutting these lines, appears to have acted somewhat after the manner of a ploughshare, the material removed coming away in a thread-like form from certain areas of the metal surface. Upon readjustment the line appeared normal and without a break. The angle made by the knife edge with the ruled surface was then increased and the effect which was produced appears in Fig. 4. Here the lines ruled are fairly symmetrical but somewhat ragged on both edges; some of the material removed from the lines appearing as minute spirals. Fig. 5, Pl. XVII., is a photograph of lines ruled with a carefully adjusted diamond at the rate of 9000 to the inch. Lines of this quality would be well suited for grating work up to 20,000 lines per inch. Two examples of finer ruling are seen in Fig. 6, the only difference between these lines and the preceding (Fig. 5) being one of pressure upon the ruling edge. Such rulings are of course much too fine for grating work.

In *conclusion* the writer may be permitted to say that the construction of a Ruling Machine is not the straightforward piece of work which this brief account may appear to indicate. Difficulties were met with from time to time which frequently necessitated a modification of preconceived ideas and intentions. The work throughout afforded but little opportunity for economy with respect to either time or labour. Practically every portion of the machine required one's best effort to be bestowed upon it; as each part was either in itself of sufficient importance to call for this or was directly related to other important parts.

It remains to express my great obligation to several gentlemen who afforded unstinted help whenever appealed to. During the early stages of the work, I was especially indebted to Mr. W. Stone, Chief Electrical Engineer of the Victorian Railways, who generously undertook the labour of cutting both the screws and grinding nuts, which required a more accurate and powerful lathe than any at my service, and who, throughout subsequent operations, was ever ready with help, suggestions and friendly criticism.

I am likewise under even greater obligation to Professor T. R. Lyle, F.R.S., who, from the initiation of the project for building a machine, interested himself and others in a variety of ways with a view to such assistance and encouragement as he considered would best help forward the undertaking. Later he induced the University Council to permit him to make provision in 1914 for housing the machine in his laboratory at the University, and for carrying on the work of its completion and improvement under favourable conditions. Since his retirement from the Chair of Physics in 1915, he has been immediately and actively associated with all the later improvements, many of which are due to him. This applies especially to the calibration and adjustment of the Ratchet wheels, and the elimination and correction of errors of the screw and its thrust plate. These operations were prolonged and tedious, but were greatly simplified by his mathematical insight and experience which, to me, were an inestimable advantage and materially reduced the mechanical work involved.

My best thanks are also due to Professor E. W. Skeats, who, during my association with his Department, unreservedly placed at my service all the facilities his workshop and laboratory afforded.

I am greatly indebted to Professor Orme Masson, F.R.S., who as President of the Professorial Board and Dean of the Faculty of Science, used his influence for the promotion of the undertaking and whose efforts made it possible for a proportion of my official time to be given to the work. To my friend, Mr. James Fawcett, of Camberwell, my heartiest thanks are due for the time and trouble he bestowed upon the preparation of the plan of the machine appearing as Plate VI., and for several minor drawings. Finally, I am fully cognisant of the fact that I owe to the University or its governing authorities, whose consideration and generosity have made it possible for me to devote so much of my time to the completion of this work during the past three years, far more than this verbal expression of my indebtedness conveys.

DESCRIPTION OF PLATES.

Plate VI.—Plan of Ruling Engine.

,, VII.—End view of Ruling Engine.

,, VIII.—Side view of Ruling Engine—Right hand.

,, IX.—Side view of Ruling Engine—Left hand.

,, X.—Front view of Ruling Engine.

,, XI.—Fig. 1. Apparatus for refining crudely separated abrasive.

Fig. 2. Apparatus for grinding the screw.

,, XII.—Fig. 1. Alundum, average diameter of grains, 1-500 inch.

Fig. 2. Alundum, average diameter of grains, 1-4000 inch.

Fig. 3. Carborundum, average diameter of grains, 1-2000 inch.

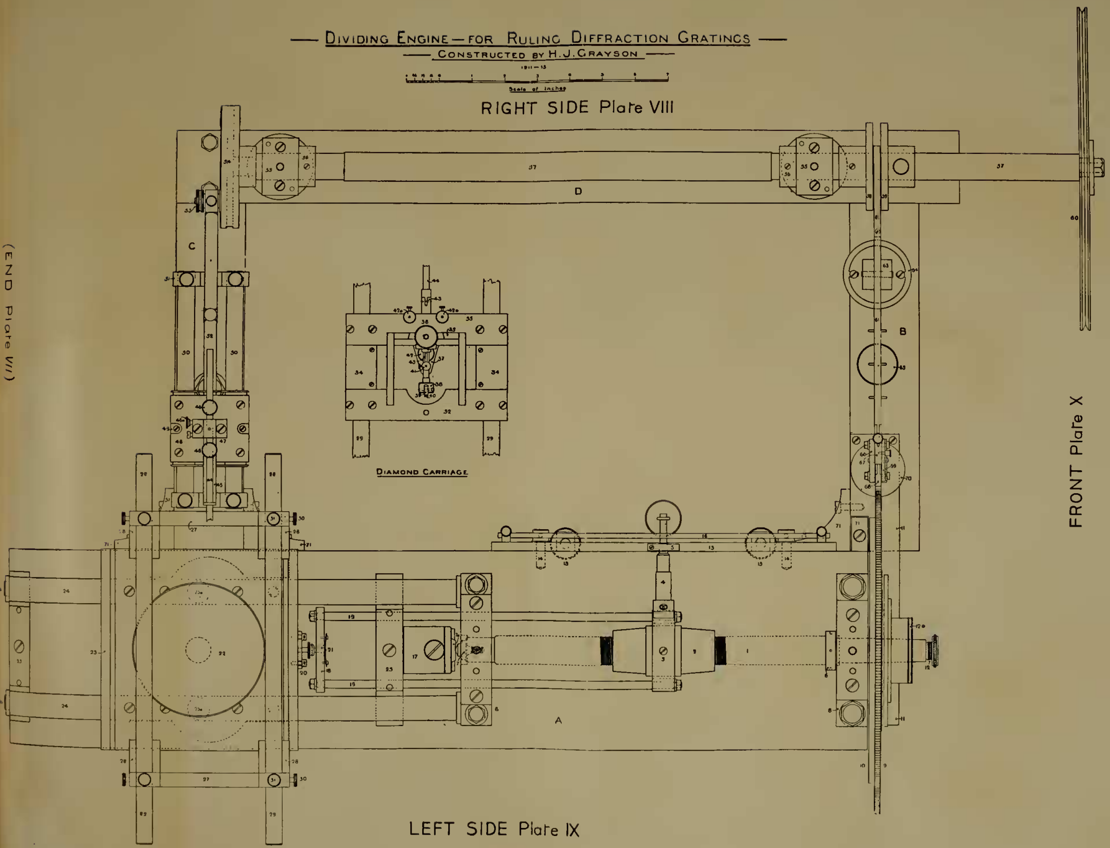
Fig. 4. Carborundum, average diameter of grains, 1-4000 inch.

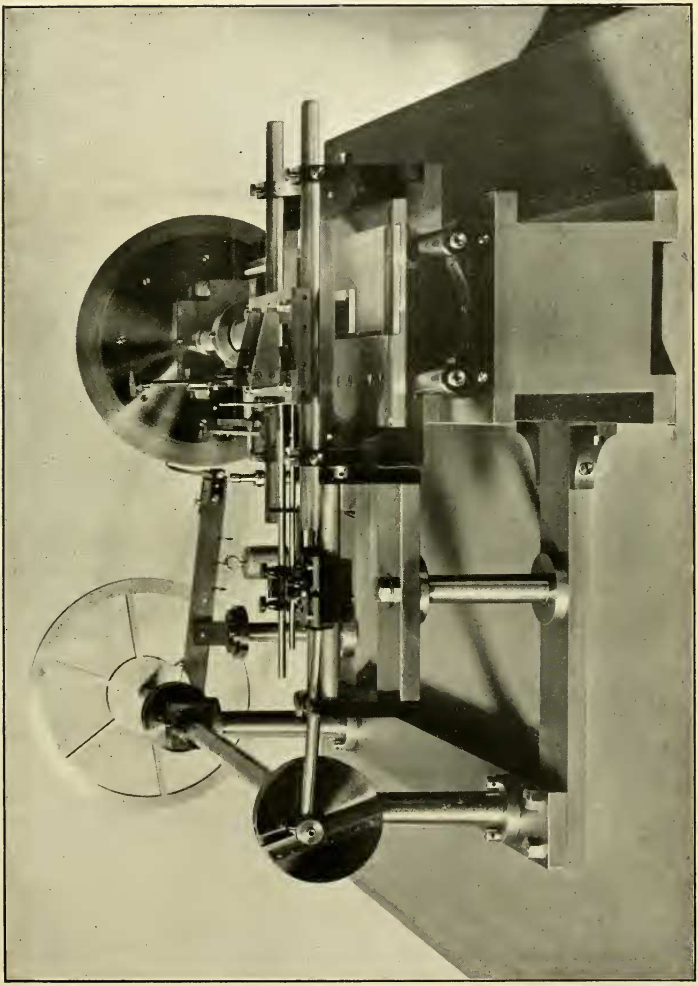
Fig. 5. Emery, average diameter of grains, 1-1000 inch.

Fig. 6. Emery, average diameter of grains, 1-4000 inch.—Figs. 1 to 6, × 75.

,, XIII.—Fig. 1. Curve indicating condition of screw prior to re-grinding.

Fig. 2. Curves showing progressive improvement during re-grinding.


DIVIDING ENGINE — FOR RULING DIFFRACTION GRATINGS
CONSTRUCTED BY H. J. GRAYSON
1911–13
Scale of Inches
RIGHT SIDE Plate VIII
(END Plate VII)
FRONT Plate X
DIAMOND CARRIAGE
LEFT SIDE Plate IX



End View of Ruling Engine (Back).